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Concerning the dissipation of electrically charged objects in the shadowed lunar polar regions

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[1] NASA recently suggested the construction of a lunar outpost at the south pole near the rim of Shackleton crater. While there are a number of advantages to such a base, the region will have periods of time when there is limited or no solar illumination - thereby reducing photoelectric and solar wind plasma currents compared to most of the lunar dayside. As a consequence of this reduction in environmental currents, we find that human systems charged by contact electrification with the regolith (e.g., roving, excavation) will have increased difficulty in removing accumulated electric charge. This situation is especially true within the cold, shadowed regions adjacent to the terminator (such as within Shackleton crater itself) where there are essentially no photoelectric currents, vastly reduced plasma currents (due to the local wake) and a highly-reduced regolith conductivity. In essence, there is no pathway for accumulated charge to ''leak away'' or dissipate, thereby creating an electrostatic hazard. Calculated dissipation timescales are found to be ~1 millisecond in the weakly sunlit terminator region and dayside but could approach 100's of seconds in the ''current-starved'' shadowed regions. **Citation:** Farrell, W. M., T. J. Stubbs, G. T. Delory, R. R. Vondrak, M. R. Collier, J. S. Halekas, and R. P. Lin (2008), Concerning the dissipation of electrically charged objects in the shadowed lunar polar regions, *Geophys. Res. Lett.*, *35*, L19104, doi:10.1029/2008GL034785.

1. Introduction

[2] The lunar terminator/polar region is an electrically active location. Driven by current balance between photoelectrons emitted by incident solar UV and anti-sunward flowing solar wind plasma, there is a substantial surface potential change from dayside-positive to nightside-negative in the region [*Manka*, 1973; *Stubbs et al.*, 2006]. At sub-solar angles (solar zenith angles) less than 90°, photoelectric currents charge the surface a few volts positive [*Freeman and Ibrahim*, 1975; *Benson*, 1977]. On the nightside at angles beyond 90°, electron plasma currents from the solar wind charge the surface negative. However, a plasma ''wake'' forms in the lunar nightside because the Moon absorbs the supersonic solar wind on the dayside, leaving a trailing plasma void in the anti-sunward directed flow [*Farrell et al.*, 2007]. Because of this trailing void, plasma currents are vastly reduced or ''choked off''. We demonstrate that this reduction in currents greatly increases the electrical dissipation time for discharging a tribo-charged object, like a roving astronaut or rover.

[3] The lunar wake has been measured directly [*Ogilvie et al.*, 1996; *Bosqued et al.*, 1996; *Halekas et al.*, 2005] and modeled with electrostatic particle simulations [*Farrell et al.*, 1998; *Birch and Chapman*, 2001a, 2001b]. Direct measurements with modern instrumentation include mid-1990 wake passages made by the Wind spacecraft at ~7 lunar radii downstream of the Moon [*Ogilvie et al.*, 1996; *Bosqued et al.*, 1996]. During these passages, the Wind plasma instruments detected a clear plasma decrease by a factor of about 50 in the central wake region compared to surrounding solar wind values and a distinct electron temperature increase (progressively increasing from the wake flank toward wake center) compared to ambient surrounding values. Later that decade, Lunar Prospector (LP) made over 6000 passes through the near-surface wake region and clearly demonstrated a very distinct bite-out in solar wind plasma density in every pass behind the moon [*Halekas et al.*, 2005]. They also demonstrated that the exponentially-decaying density profile and linearly-increasing electron temperature in the wake could be explained via a modified self-similar plasma expansion from the wake flank into the void region.

[4] Figure 1 shows a model of the expected plasma electron density in the region above the lunar plasma sheath and at the surface combining the *Manka* [1973] surface charging analysis with the *Halekas et al.* [2005] modified self-similar model of the lunar nightside wake region (same model as *Farrell et al.* [2007]). *Manka* [1973] provided a 1-D surface current balance formalism to quantify the lunar surface boundary potential that defines the inner edge of the lunar plasma sheath. This formalism requires an input pre-sheath plasma density profile, and *Halekas et al.* [2005] derived a nominal wake density profile that fit the extraordinarily large number of LP passages. Downstream of the terminator, in the wake region, the electron density above the sheath is reduced compared to nominal solar wind values of ~5 el/cm^3. This reduction is due to absorption of the flowing plasma at the lunar front-side and the development of an ambipolar E-field along the wake flanks that acts to retard electron motion and enhance ion flow into the void [*Ogilvie et al.*, 1996; *Farrell et al.*, 1998; *Halekas et al.*, 2005]. At the surface, electron densities are further reduced due to the retarding nightside surface potential, ϕ <0, which allows only the most energetic portion of the electron population to be incident with the surface. Due to these dual electric potential steps (wake ambipolar potential and surface sheath poten-

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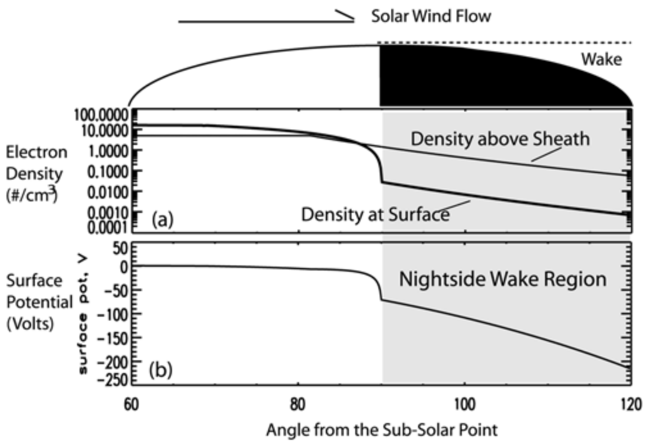

Figure 1. The (a) electron density and (b) surface potential as a function of sub-solar angle. The electron densities decrease substantially in nightside regions due to the lunar wake trailing the Moon and as a consequence, the surface potentials becomes large and negative in the nightside region.

tials), only the most energetic electrons at the tail of the solar wind electron energy distribution are capable of getting all the way onto the nightside lunar surface. We thus find that the nightside surface densities are as low as a few hundred electrons/m^3 from a solar wind that has an initial ambient background of 5×10^6 electrons/m^3 - an electrostatic ''filtration'' effect exceeding 5000 to 1.

[5] It becomes clear that ambient environmental currents are ''choked off'' in the shadowed regions directly adjacent to the terminator: The lack of sunlight creates a complete loss of photoelectron currents and the wake creates a substantial reduction of solar wind plasma currents by factors of 10^4. The lunar surface is essentially an insulator due to the loss of conductivity with nightside temperatures ($\sigma \sim 10^{-14}$ S/m [*Carrier et al.*, 1991]). As a consequence, there is no significant charge reservoir to neutralize any charge buildup that develops from either natural or anthropogenic processes.

2. Charge Dissipation

[6] Consider an object such as an astronaut walking on the lunar surface near the terminator. This object can become charged via contact electrification with the surface (charged via tribo- or frictional electrification). This charging system is modeled as a capacitor that is initially connected to a tribo-electric current source (see Figure 2). We initially assume the moving astronaut is collecting positive tribo-charge to a value of Q = CV, with C being the capacitance and V being the positive astronaut potential relative to the ambient plasma. For an object of ~1-meter in radius (roughly like an astronaut), the bulk capacitance is approximately $4\pi\varepsilon_o r \sim 100$ pF.

[7] If the astronaut stops moving, then they will also stop tribo-charging, which is equivalent to opening the switch in Figure 2 connecting the capacitor to the tribo-electric current source. There are two paths to discharge the capacitor plate: (1) to ground and (2) the surrounding plasma. Because the lunar surface is highly resistive (R_g large), the ambient plasma currents, I_{amb}, become the dominant source to neutralize the charge on the astronaut. The time to dissipate the excess positive charge from the astronaut – the relaxation time - is $\tau^+ \sim Q/I^-$, where I^- is the negative (electron) current attracted to the object of positive potential V. In the terminator region, the dominant source of I^-_{amb} is the solar wind plasma electron population with thermal velocity, $v_{the} = (2kT_e/m_e)^{1/2}$. Within a few Debye lengths of the object, this ambient electron current, I^-_{amb}, is attracted to positively charged object and is enhanced in the vicinity of the object by $I^- = I^-_{amb}\,(1 + eV/kT_e) \sim I^-_{amb}\, eV/kT_e$ for $eV > kT_e$ [*Goertz*, 1989]. In essence, there is a ''gain'' in the ambient electron current in the region under the influence of astronaut potential, V, with the current gain, g, varying as $\sim eV/kT_e$. This electron current is drawn from the plasma and attracted to the astronaut and is represented in Figure 2 by the current source g I_{amb}. For completeness, the equivalent circuit in Figure 2 should also include an ambient ion current source, but ions are repelled in the vicinity of the astronaut by a factor of exp $(-eV/kT_i)$ [*Goertz*, 1989] and thus do not enter substantially into the formalism. Since V = Q/C, the electron current, I^-, to dissipate the positively charged object is $I^- \sim I^-_{amb}\, eQ/kT_eC$.

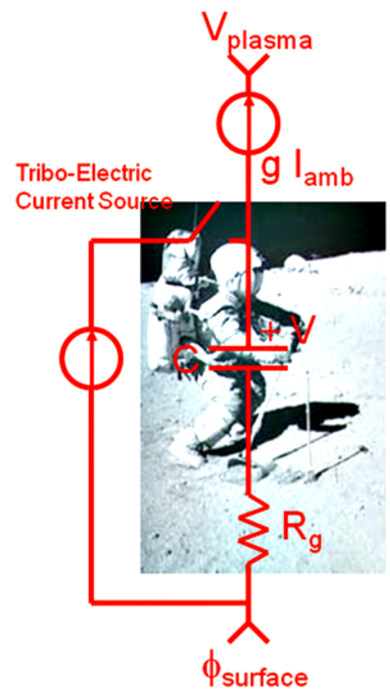

Figure 2. The equivalent electric circuit of an astronaut moving on the lunar surface. The astronaut can be modeled as a capacitor that collects charge during each step via contact electrification (or tribo-charging). As a consequence, the plate on the capacitor charges to +Q with a voltage +V = +Q/C. The capacitor electric field tries to draw an equal but opposite charge −Q through the highly resistive ground, R_g, in order to make the object (astronaut) charge neutral. However, ambient plasma currents react faster than the ground currents (plasma on time scales τ^+ in equation (1)), providing a neutralizing electron current to the +V plate in direct proportion to the voltage on the plate (gain, g, is eV/kT_e).

Table 1. Anticipated Ambient Plasma Electron and Ion Currents to Neutralize Any Charge Buildup on Time-Scale, τ

	Location and Charge of Object			
	Terminator (85°)		Nightside (120°)	
	Positive	Negative	Positive	Negative
n_e (m^{-3})	$5 \cdot 10^6$		700	
kT_e/e (eV)	10		35	
n_i (m^{-3})		$5 \cdot 10^6$		f700
KT_i/e (eV)		10		10–35
C (pF)	100	100	100	100
A (m^{-2})	10	10	10	10
J_{amb} (A/m^2)	$-1.6 \cdot 10^{-6}$	$+3.5 \cdot 10^{-8}$	$-4 \cdot 10^{-10}$	$+f4 \cdot 10^{-10}$
τ (s) – Astronaut	$8 \cdot 10^{-5}$	$3 \cdot 10^{-3}$	0.9	0.9/f
τ (s) – 0.1-m Boot	$8 \cdot 10^{-4}$	$3 \cdot 10^{-2}$	9	9/f

As a consequence, we can derive a dissipation time to remove excess positive charge as

$$\tau^{+} \sim (kT_e/e)(C/|J^{-}_{amb}|A) \tag{1}$$

where A is the current collection area and J^{-}_{amb} is the ambient electron current density equal to I^{-}/A. The current collection area for an astronaut is approximately $A \sim 10\ m^2$. Via a parallel argument, the dissipation time for a negatively charged object is

$$\tau^{-} \sim (kT_i/e)(C/|J^{+}_{amb}|A) \tag{2}$$

where T_i is the positive ion temperature and J^{+}_{amb} is the ion ambient current drawn to the negative object placed at the surface. We note that the dissipation time is independent of the initial charging value, Q, as along as $|eV| > kT_{e,i}$ which is applicable for the large voltage tribo-electric charging cases.

[8] Table 1 shows the electrical dissipation rates for both terminator (near 85° from the sub-solar point) and deeper nightside regions (120° from the sub-solar point or 30° nightside of the terminator). At the near-terminator location, surface-generated photoelectron currents are reduced due to the oblique incidence of sunlight. Hence the dominant electron and ion currents are from the passing solar wind, with surface-incident fluxes defined by $n_e v_{the}$ and $n_i v_{thi}$. The surface potential, ϕ, is near zero and thus has minimal modification on the thermal plasma. Consequently, $J^{-,+}_{amb}$ is on the order of 0.04–2 $\mu A/m^2$ which is enough natural current in the environment to neutralize any anomalous charge buildup on time scales of a millisecond. Similar fast dissipation times are also found for the mid-latitude dayside regions, with any positive charge buildup neutralized by the more dense but colder photoelectrons found in the sheath and any negative charge buildup neutralized by the direct solar wind ion flow. On the dayside, the ambient environmental currents easily neutralize anomalous charge build up.

[9] However, in nightside lunar regions, the situation is very different since there is a lack of environmental electrical currents to dissipate the charge buildup. Consider first the situation of a positive charge buildup located ~30° downstream from the terminator (120° from the subsolar point). Lunar Prospector in orbit between 20–115 km clearly detected a distinct plasma void trailing the Moon [*Halekas et al.*, 2005], with electron densities exponentially-decreasing to a few percent of solar wind levels and electron temperatures steadily rising to 6–7 times ambient solar wind levels in the central void region. These observations were found to be adequately modeled with a modified self-similar plasma expansion formalism [*Halekas et al.*, 2005]. The self-similar plasma expansion density is applied in the model shown in Figure 1a, labeled as "Density above the sheath" in the nightside wake region. However, because the surface wants to maintain current balance (and thus retard these warm electrons), the surface will charge strongly negative [*Manka*, 1973], as indicated in Figure 1b. As a consequence, only the most energetic wake electrons overcoming the repulsive surface potentials are capable of reaching the surface, and the reduced electron density due to surface repulsion is indicated in Figure 1a as "Density at the surface". Surface electron density values are $\sim 700/m^3$ near 30° nightside of the terminator. The corresponding ambient electron currents at surface level are thus $\sim 4 \times 10^{-10}\ A/m^2$, increasing the dissipation time for any positively charged, large object to nearly a second (see Table 1). Note that the dissipation time for a positively charged object has increased by $\sim 10^3$ compared to sunlit regions.

[10] For an anomalous negative charge buildup on the nightside, the situation is more complicated. The object will require ambient ion currents to neutralize the build-up. According to surface charging models [*Manka*, 1973; *Stubbs et al.*, 2006; *Farrell et al.*, 2007; T. J. Stubbs et al., Dependence of lunar surface charging on ambient plasma conditions and solar irradiation, submitted to *Journal of Geophysical Research,* 2008], the surface will charge negative to repel electrons and draw in ions from the passing solar wind, such that there is current balance between ions and electrons. In this case, the positive ion current at surface is also $J^{+}_{amb} \sim 4 \times 10^{-10}\ A/m^2$ making the dissipation times also on the order of a second.

[11] However, more advanced models [*Crow et al.*, 1975; *Birch and Chapman*, 2001a, 2001b; *Farrell et al.*, 2008] suggest that there is a break in plasma quasi-neutrality due to the kinetic nature of the plasma expansion process into the trailing solar wind void formed downstream of the Moon. Specifically, thermal electrons should migrate across the wake flank into the void ahead of the slower, more-massive ions. As a consequence, an ambipolar E-field forms to force the ions to catch up. However, there is evidence in these studies that the ions never fully catch up and that there is an "electron cloud" [*Crow et al.*, 1975] that propagates into the void ahead of the expanding quasi-neutral plasma. Any negatively-charged object immersed in this electron cloud will have no/few ions to neutralize its charge build-up. In Table 1, we represent this ion-diminishing factor by the variable f (in column 4) representing the ratio of ion-to-electron densities. If the plasma is neutral throughout, then $f \sim 1$. However, f can be <0.1 in electron cloud regions [*Crow et al.*, 1975; *Birch and Chapman*, 2001a, 2001b; *Farrell et al.*, 2008], increasing the dissipation times for negative charge accumulations to over 10 seconds.

3. Implications

[12] While the calculations for nightside regions apply to locations 30° from the terminator, they can apply equally as well in large craters that lie close to the terminator/polar

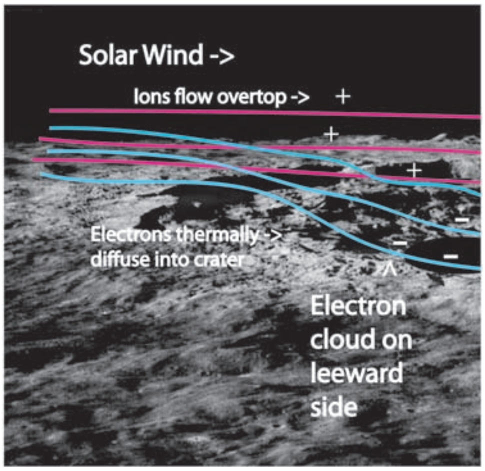

Figure 3. Illustration of the solar wind plasma expansion into an unlit crater at the poles. The low-mass electrons have a greater thermal expansion velocity (~2000 km/sec) which allows them to expand into the crater ahead of the slower ions (expanding inward at the sound speed of 10's of km/sec). As a consequence, the leeward side of the crater (with a normal parallel to the solar wind flow) is immersed in an electron-rich cloud making the ion-to-electron density ratio, f, substantially less than unity.

regions, such as Shackleton or Shoemaker crater. Any object moving into such permanently-shadowed craters will lose photoelectric currents and will have vastly reduced plasma currents since the solar wind will primarily flow over the crater top. This loss of solar wind plasma will be particularly enhanced on the "leeward" side of the crater, that part of the crater wall that has a surface normal parallel to the solar wind flow [*Farrell et al.*, 2007]. Figure 3 illustrates the situation and suggests there is a solar wind orographic effect creating a mini-wake. This leeward region will most likely reside in an electron cloud, since solar wind electrons will thermally-diffuse into the crater ahead of the more massive ion which have yet to be influenced by the effect of the ambipolar field (created by the loss of charge quasi-neutrality) [*Farrell et al.*, 2008]. Any object that charges negative on this leeward-facing crater wall will have substantial difficulty dissipating its charge due to the lack of ions in the crater plasma.

[13] Since the object capacitance varies with effective radius, r, and the current collecting area varies as $\sim r^2$, the dissipation time varies as $\sim 1/r$. Hence, charge dissipation for smaller objects can be much longer. For example, we have implicitly assumed that any tribo-charge generated by a walking astronaut is distributed over the entire quasi-conducting space suit. However, if this tribo-charging is limited to the astronaut boot region (due to a poorly conducting suit), the effective radius of the tribo-charging/current collecting region is then reduced by about a factor of 10 compared to the entire astronaut suit. In this case, dissipation times are on the order of 10's to 100's of seconds (see Table 1), depending upon the charge polarity and ratio of ion-to-electron concentration (f).

[14] In general, the overall charge build-up on a system can be described by $dQ/dt = S_t(t) - Q/\tau$, with $S_t(t)$ being the source of triboelectric charge which is assumed to vary with time and $-Q/\tau$ representing the dissipation in a plasma environment. If $S_t > Q/\tau$ then excess charge will accumulate.

[15] In applications to the lunar nightside, the calculated dissipation times on the order of a second or above should raise some concerns for human exploration. Specifically, for a moving astronaut, each step that is in contact with the surface will increase the tribocharge on the space suit. Since the cadence of the human gait is about a second, walking in nightside/wake regions will allow the charge to accumulate for each step without substantial inter-step dissipation. For example, the charge associated with a set of consecutive steps by an astronaut can be modeled as a set of delta-functions with peak tribo-charge Q_o, with each delta function separated by about 1 second in time. After charging up to value Q_o, dissipation creates an exponential decaying function in time, with a 1/e folding time of τ. If τ is large (>1 second), the astronaut never completely discharges between steps and there will be a net accumulation as each step adds to the residual, accumulating charge left by the previous steps. In contrast, in sunlit regions, the dissipation times are small (at millisecond levels), virtually guaranteeing complete charge neutralization between steps. Hence, charge buildup was not an issue during well-sunlit EVAs taken by the Apollo astronauts, but could be a larger issue for astronauts hiking near/into the Shackleton crater region. Using a lunar rover vehicle into the shadowed crater could be especially challenging given that the vehicle would essentially charge in a continuous fashion (S = constant), thereby obtaining large charge values with little/no dissipation. A somewhat impractical approach would be to stop the rover on time scales of a few seconds and let the (highly reduced) ambient currents dissipate the rover charging to safe levels.

[16] We note that in a low current environment, the astronaut or rover will not build up charge indefinitely – the charging object (especially a continuous-charging rover) will attempt to create its own current to reduce its own potential. If a rover charges too greatly, it will start to emit electronic secondary products, especially electrons for a negatively charged object, which will attempt to offset the build-up of charge. Additionally, if an astronaut or rover has tribo-charged to great excess, the regolith (surface dust) just passed over will have an equal but opposite tribo-charge – and be drawn to the astronaut or roving system. This oppositely-charged dust adheres in an attempt to remediate the excess charge in the astronaut. These processes were not included here but will act as natural limits to the charging process.

4. Conclusions

[17] The fundamental phenomenon that allows the accumulation of large amount of excess charge to occur in nightside regions is the lack of an electrical reservoir of charge – an effective electrical "ground" – that would normally act to remediate any charge build-up. In the frigid shadowed regions (like within Shackleton crater itself), the surface conductivity is expected to be very low (making R_g in Figure 2 very large) and the region is also starved of photoelectric and plasma currents. The lack of an available, common charge reservoir then allows objects to maintain any tribocharge build-up and thus to "float" at potentials

that may differ significantly from surrounding objects. On the dayside, photoelectrons, solar wind ions, and the natural lunar ionosphere all act as the remediation source.

[18] We recommend that careful consideration be paid to electrical charging and dissipation issues for any EVAs into the shadowed regions. Because of excess tribo-charge retention, a roving astronaut, excavation equipment, etc may become an electrostatic discharge (ESD) hazard and a dust attractor. To partially mitigate the charging hazard and to obtain firmer predictions of dissipation, we recommend that the lunar wake electron cloud region that is responsible for the slowest dissipation times be studied in detail. Specifically, electron and ion density and size extent should be determined in order to quantify the geometric factor f representing the ratio of ion-to-electron density in the ambipolar region. Such an investigation could be performed by an orbiting spacecraft or landed package containing plasma electron & ion spectrometers and DC E-field system.

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